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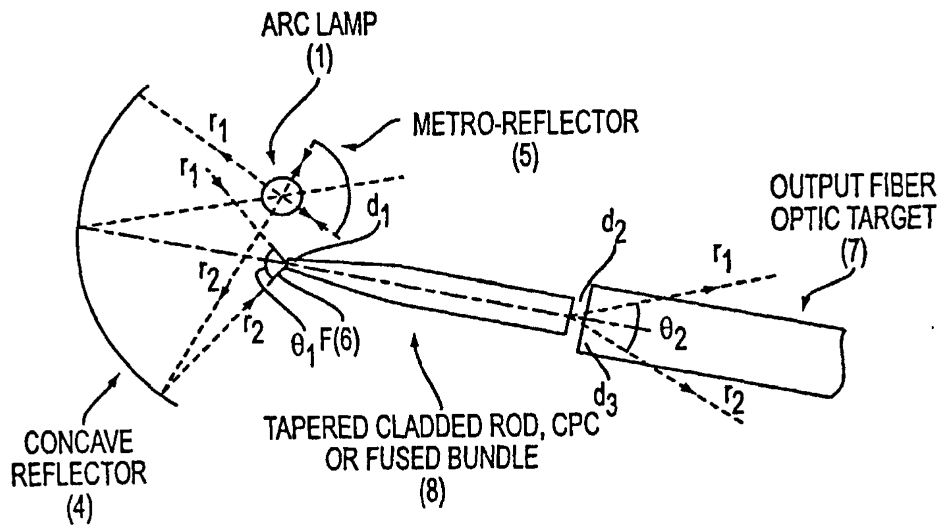
(54) Title: IMPROVED COUPLING OF LIGHT FROM A SMALL ARC LAMP TO A LARGER TARGET

(57) Abstract

A light guide (8) is used to couple as much light as possible from an imaging source (1) having a large numerical aperture into a fiber optic component (7) with a relatively smaller numerical aperture. A tapered cladded rod, tapered fused bundle of optical fibers, tapered hollow reflective tube, CPC or negative lens when used as a light guide, provides for efficient coupling of light into a fiber optic component without loss of flux density. Such a system is especially advantageous when used with an imaging source that produces a very small image spot size with high numerical aperture, such as one producing a 1:1 image like a spherical off–axis reflector.



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IMPROVED COUPLING OF LIGHT FROM A SMALL ARC LAMP TO A LARGER TARGET

Field of the Invention

The invention is in the field of systems for collecting and condensing electromagnetic radiation and coupling that radiation into a target.

Background of the Invention

It has long been a goal in the field of fiber optic technology to develop a system for more efficiently collecting and condensing electromagnetic radiation from an incoherent light source, approximated by a point source. Conventional systems have attempted to direct radiation originating from a conventional incoherent light source into a small spot size without an accompanying decrease in radiation flux.

Commonly, two approaches have been taken in the development of such systems. The first involves the use of condensing lenses between the light source and target. Such condenser lenses typically have several drawbacks in that they often are relatively costly, space consuming, inherently difficult to align, and they create chromatic and spherical aberrations. The other common approach is the use of ellipsoidal reflecting mirrors. These reflecting systems are also very costly, and they have the inherent drawback that they cause a natural magnification of the image resulting in a reduction in the flux density to the target.

The most common prior art system involves a parabolic reflector used together with a lens as shown in Figure 5. The parabolic reflector 9 forms the housing of the lamp 1 with

surfaces coated with either aluminum or silver. The gas is sealed into this housing using a window. The arc of the lamp is placed at the focus of the parabola which causes the output beam to be comprised of parallel rays. A reflective coating of aluminum or silver reflects radiation from UV through visible to infrared. As a result, for applications like medical illuminations, a visible filter is needed to filter out unwanted UV and infrared radiation. Usually, a transmission filter is used which can not be made with sharp cutoff of wavelength. The resulting output therefore is comprised of more than the desirable amount of UV and infrared radiation. When a reflective filter is used, the distance between the lamp and the focusing lens has to be increased to accommodate the filter. This reduces the coupling efficiency of the system. To couple the light into an output device 7, such as an optical fiber bundle, a focusing lens 10 is typically used to redirect the parallel beam into a small spot. The output numerical aperture from the lens is matched to the numerical aperture of the fiber bundle to achieve the maximum possible coupling efficiency. Due to the intrinsic nature of the combination of the parabola and focusing lens, the magnification of the arc onto the bundle is not constant over the whole aperture. As a result, the output spot size is always larger than the arc of the lamp itself. This mechanism results in a decrease in the maximum possible brightness or flux intensity at the focusing point. Together with aberrations created by the focusing lens, such systems produce an output with

a spot size significantly larger than the arc gap, and a distribution which is non-uniform.

Figure 6 illustrates another common configuration for focusing output from an arc lamp into a fiber bundle. In this case, the arc of the lamp is placed at one focus of the ellipsoidal reflector 3 with the electrode placed along the major axis of the ellipsoid. The output fiber 7 is placed at the target 6 which is located at the other focus along the major axis. The size of the ellipsoidal surface and the distance between the two foci determine the numerical aperture of the output beam. Due to various paths for light to go from one focus to the other, the magnification is not constant for all rays. As a result, the output spot size at the other focus is usually a few times larger than the arc itself. This inherent magnification again reduces the brightness of the arc.

U.S. Patent No. 4,757,431 to Cross et al., the specification of which is herein incorporated by reference, discloses a collecting and condensing system which utilizes an off-axis spherical concave reflecting system to enhance the amount of flux density at the target point over previous ellipsoidal reflecting systems. The layout of such a system is shown in Figure 7. This system, while allowing increased flux density derived from its inherent 1:1 image magnification at the target spot, has the drawback in that its flux concentration efficiency decreases with the linear off-axis distance between the target 6 and the arc lamp 1. Any attempt to limit such flux loss by minimizing the

off-axis displacement is constricted by the physical size and shape of the illumination source and target or fiber optic output device 7. U.S. Patent No. 5,430,634 to Baker et al., the specification of which is also herein incorporated by reference, discloses a variant of the off-axis reflecting system as disclosed in U.S. Pat. No. 4,757,431 wherein a concave toroidal reflector is employed in place of the concave spherical reflector 4.

Tapered rods and cones are commonly incorporated into the input light post of endoscopes for maximizing the collection of light from a large diameter source and transforming the collected light into a smaller spot size and a larger numerical aperture. Typically these configurations are highly inefficient because the cone length is too short for optimizing the transformation both spatially and angularly. U.S. Patent No. 5,729,643 to Hemlar et al. discloses the use of a tapered optical fiber having an input core diameter which tapers down to a smaller output diameter in order to focus light into a smaller spot size.

As shown by U.S. patent 5,680,257 to Anderson, beam integrating optics using lenses and conical integrators and reflectors to condense light into a small spot size with increased angular divergence are also known in the art. All of these previous systems, however, necessarily produce an increase in the numerical aperture of the light. Therefore, such systems are inefficient when used to couple light into an optical fiber.

The resulting increase in numerical aperture, or divergence, of the light during efforts to decrease the spot size causes a large portion of the collected light to exceed the numerical aperture of an output optical fiber placed at the image point. Thus, a considerable proportion of incident light at the image point cannot be transmitted by the fiber. There remains a need in the art for improvements in coupling light from light collecting and condensing systems.

Summary of the Invention

In the field of the present invention, the incoherent light from the arc lamp 1 is generally desired to be imaged onto a target 6, such as the end of a single fiber or fiber bundle. Coupling of the light from the condensing and collecting systems into an optical fiber is optimized when the numerical apertures of the reflector or condenser lens and the fiber optic target are equal. As a rule, the numerical aperture of the light output from the fiber will be the same as that of the reflector/lens system or the fiber, whichever is smaller. This is because an optical fiber can generally be said to have an intrinsic numerical aperture which represents the highest propagation angle a beam of light can have and be completely contained within the optical fiber. Any time the light passing through an optical fiber exceeds the numerical aperture of the fiber, leakage of light will occur. This fact becomes very important whenever an optical fiber is bent, typically causing a localized decrease in the fiber's effective numerical aperture. Thus, it is desirous

to have high flux density light passing through an optical fiber which has a numerical aperture less than the numerical aperture of the fiber.

On the other hand, to redirect the maximum amount of light flux from the arc lamp onto the target spot requires use of a primary mirror with as large a numerical aperture as possible. Commonly the high numerical aperture light from the mirror/lens will be larger than that of the fiber optic or fiber optic bundle at the target spot. Because of the transmission limits described above, this means a significant portion of the light reaching the target will not be transmitted by the output fiber and will be lost.

The invention improves upon prior art for coupling light into large diameter targets. It provides a mechanism for coupling the light of high numerical aperture into an intermediate optically transforming device such that the light collected from the lamp from any condensing and collecting system is transformed into an output having a smaller numerical aperture and larger spot size for efficient coupling to the input end of a large diameter single fiber or fiber bundle matched in diameter and numerical aperture. The net result is higher efficiency and output relative to prior art systems coupling light into the same target.

Tapered rods and cones are commonly incorporated into the input light post of endoscopes for maximizing the collection of light from a large diameter source and transforming the collected

light into a smaller spot size and a larger numerical aperture. Typically these configurations are highly inefficient because the cone length is too short for optimizing the transformation both spatially and angularly.

Tapered hollow tubes with reflective interior surfaces are also commonly used to "funnel" light into a small spot size from a source. Such hollow tapered tubes work like a funnel in that they have an aperture at either end, one aperture being larger than the other. The tube takes light in at the larger aperture and smoothly condenses it by reflection inside the conical surface into a small spot size and larger divergence when it leaves at the smaller aperture. These types of optical devices are commonly incorporated in LCD projectors, DMD projectors, and the like.

Another species of light guide with specific applicability to the present invention is a specialized form of the tapered hollow tube known as the compound parabolic concentrator, or "CPC." CPCs are like the tapered hollow tube, but their interior reflective surfaces are parabolic, or curved. Such paraboloid surfaces have been found to be effective in concentrating light emitted from a large source at a distance into a small spot size. Therefore, CPCs find common application in collecting solar rays for heating or generating electricity. For such applications, the input end of the CPC has a larger cross section than the output end, and light emitted from the output end has a much larger numerical aperture.

Solid glass CPCs can also be configured to produce similar results. Alternatively, a lens can be employed as the light guide. As shown in U.S. patent 5,680,257, lenses are commonly employed to condense light into a small target spot. Again, such use necessarily results in an increased NA, or divergence, of the light.

A light guide in the form of a single tapered cladded rod or cone, a tapered fused fiber optic bundle, a reflective tapered hollow tube, a compound parabolic concentrator, a negative lens, or a combination thereof, placed at the image point of the system can maximize the transmission of light through the final fiber optic target. The present invention makes use of such prior art devices as a light guide by utilizing it in a manner reverse to their typical manner of use. The above devices are positioned whereby the incident light directed from the optical collection system, such as from any of the aforementioned prior art systems, is increased in spot size and decreased in angular distribution to maximize the amount of light ultimately collected and able to be transmitted through a fiber optic device.

Brief Description of the Drawings

Fig. 1 is a schematic illustration of one embodiment of the present invention using an off-axis toroidal concave reflector as the primary collector.

Fig. 2 is a schematic illustration of one embodiment of the present invention using an off-axis ellipsoidal concave reflector as the primary collector.

Fig. 3 is a schematic illustration of one embodiment of the present invention using an on-axis extended ellipsoidal concave reflector as the primary collector.

Fig. 4 is a schematic illustration of one embodiment of the present invention showing a negative lens being used as a light guide.

Fig. 5 is a schematic illustration of a prior art condenser and collector system employing a parabolic concave reflector and focusing lens.

Fig. 6 is a schematic illustration of a prior art condenser and collector system employing an ellipsoidal concave reflector.

Fig. 7 is a schematic illustration of a prior art condenser and collector system employing a toroidal concave reflector with the source and target located in an off-axis relationship.

Detailed Description of the Invention

Embodiments of the invention generally are comprised of a short arc lamp 1, as shown in the figures. Suitable arc lamps include lamps producing arc gaps of up to about 8 mm, including but not limited to Xenon, Mercury, Mercury-Xenon, AC metal halide, and DC metal halide type lamps ranging in power anywhere from 100 to 500 watts. Experiments have indicated that acceptable results have been achieved using 1 mm, 1.5 mm, 2 mm, 3 mm, and up to 6 mm arc gaps from 100 and 500 watt Xenon and 250 and 270 watt metal halide arc lamps.

The arc lamp 1 is used in conjunction with any known primary collection system. Figure 2 illustrates one embodiment of the

invention where an off-axis ellipsoidal concave reflector 2 is used as the primary collector. Figure 3 illustrates another embodiment of the invention where an on-axis ellipsoidal concave reflector 3 is used as the primary collector.

Figure 1 illustrates one preferred embodiment of the invention where an off-axis spherical concave reflector 4 is used as the primary collector. In any of the above embodiments, a retro-reflector 5 may be employed to increase light flux to the primary collector 2, 3, or 4, as shown in Figures 1, 2, and 3, respectively. The primary collector and retro-reflector 5 can optionally be coated with dielectric material, aluminum, or silver for circumstances where a specific wavelength of light is desired to be collected or where broad band electromagnetic radiation is so desired. For example, where the radiation is to be used for purposes of illumination with visible light, the mirror can be coated with a multi-layer dielectric coating that reflects only the visible light and rejects the UV and IR radiation. The output would be a visible light only having a color temperature dependent upon the source, such as a xenon lamp with color temperature on the order of 6000 degrees Kelvin. Such light output is particularly suitable for visual applications such as in surgical illumination.

The light from the lamp 1 is directed by the primary collector 2, 3, or 4 to a target spot 6. In prior art systems as depicted in Figures 5, 6, and 7, a light transmitting output device 7 is placed at the target spot 6. In the present

invention, a device 8 for transforming the numerical aperture and spot size of the collected light, or "light guide," is placed at the target spot to transform light to a spot size and numerical aperture matched to that of the output device 7. For example, Figures 1 and 7 differ by light guide 6 which enables the collected light to be more efficiently inputted and transmitted through fiber optic 7, thereby, increasing the amount of usable light at the distal end of fiber optic 7.

Different optical devices may suitably serve as the light guide 8 in embodiments of the present invention.

The use of a tapered cladded rod as the transforming device 8 in the current invention provides for optimal transformation of the light's angular distribution. The spatial distribution conversely is not optimized because the output from a cladded rod is typically not uniform and is comprised of concentric rings of light. However, if the final output device 7 is a randomized fiber bundle, the light is scrambled at the output of the fiber bundle and there is no negative consequence of having an input that is nonuniform in spatial profile. A tapered fused bundle can alternatively be used as the light guide, but a tapered fused bundle is less efficient in the transmission of light to the final target for the same length of glass as a tapered rod. However, the output from the tapered fused bundle is spatially randomized and more uniform. Therefore, the light from a tapered fused bundle acting as the transforming device 8, or light guide, is more readily coupled into a large diameter single fiber to

produce a uniform output from the single fiber. If a shorter fused bundle taper is used, the overall transmission loss can be minimized. A fused bundle taper provides better spatial uniformity for a shorter length because the small diameter, typically less than 80 microns, of the individual fibers of the fused bundle taper transform the angular and spatial profile within approximately 30 diameters of the individual fiber.

A tapered hollow reflective tube, or a CPC, can also be employed as the light guide in embodiments of the present invention. The smaller aperture of the tube or CPC would be placed at the target spot such that the light is transformed to a NA and an output diameter approximately equal to that of the output device.

This class of light guides can be coated to reflect only certain wavelengths of light, such as with a multi-layer dielectric coating. A coated tapered hollow reflective tube or coated CPC would then provide the user with the ability to filter unwanted light if the collecting and condensing system employed did not have this capability. The output from a tapered hollow reflective tube and a CPC normally has a non-uniform spatial profile.

Another embodiment of a light guide of the present invention is depicted in Figure 4. A negative lens 11, when used as the light guide, redirects rays r_5 and r_6 to the output device 7 such that the rays are deflected more to the normal of the target spot surface. In the preferred embodiment, a lens with a leading flat

face is used. This deflection results in more efficient coupling due to the smaller NA and larger spot size. Negative lenses used as the light guide, like tapered cladded rods and tapered fused bundles, can act as filters of unwanted wavelengths of light. When using a lens as the light guide, it should be noted that the light emanating from the guide will be spatially non-uniform and may contain spherical aberrations. Use of a negative lens in combination with a fused bundle will improve the spatial uniformity.

In alternative embodiments of the present invention, a fused bundle or cladded cylindrical rod having an NA and diameter similar to that of the output device can be placed between the light guide and output device such that the light from the light guide is transferred through the rod or bundle to the output device. A design incorporating either of the two would have advantageous practical implications. The spatial profile from the output of a fused bundle of optical fibers is uniform, even if the input profile was non-uniform. Therefore, when a light guide which produces a non-uniform spatial profile is used, such as, for example, a tapered cladded rod, a negative lens, or tapered hollow reflective tube, such a fused bundle can provide a uniform input to the fiber optic output device. A cladded rod used for such a purpose would be especially advantageous if the fiber optic output device was particularly sensitive to heat, and therefore needed to be removed from the heat present at the target spot.

One skilled in the art will appreciate that the particular type of light guide employed in embodiments of this invention will vary according to the purpose and the particulars of the output device and condensing system, including; whether light filtering is desired, whether the fiber optic output device is particularly sensitive to heat, whether a uniform spatial profile is necessary, and whether the specific system has size restraints.

For maximum collection of light at the target spot 6 in the embodiment shown, two conditions are preferred: (i) the input diameter of the target spot 6 must be at least two (2) times the length of the arc gap to assure collection of greater than 80% of the total light at the target spot 6 and (ii) the numerical aperture ("NA") of the primary collection system at the target spot 6 should be maximized. The latter is accomplished by using a primary collector with the largest possible NA. However the output device 7, such as a single fiber or a fiber bundle, may have a lower NA than the NA of the primary collector. For example, the light at the target spot coming from the primary collector might have an NA from 0.7 to 0.8, and the output fiber or bundle about 0.5 which is typical of fiber bundles. This mismatch in NA, if the light is coupled directly to the output fiber, will result in a large loss of light and the generation of unwanted heat. In the preferred embodiments of this invention discussed below, a transforming device 8, in the form of tapered fused bundles and tapered cladded rods, transforms the large NA

light emerging from the primary collector into a smaller NA as shown by rays r_1 and r_2 in Figure 1.

From basic optics, if the diameter of a light guide is increased along its length through tapering of the glass, the angle of illumination, θ, will decrease, and thus the numerical aperture, will also decrease. Therefore, by tapering a fused bundle or cladded rod from a smaller input area into a larger output area, the angle of illumination is adjusted to match that of the output device 7. In terms of angle of illumination, θ, diameter of the fiber optic cross section, d, and numerical aperture, NA, the inherent relationship:

$$NA_1 \times d_1 = NA_2 \times d_2 \qquad (1)$$

$$\text{where } NA_i = \sin(\theta_i/2) \qquad (2)$$

applies. In the present invention, as depicted in Figure 1, relationships (1) and (2) are being manipulated by the light guide to optimize the amount of light for the NA and diameter of the fiber optic output device.

The output of the lamp 1 is imaged to the target spot 6 using any known means, such as a spherical concave, toroidal, or ellipsoidal primary mirror systems. In the preferred embodiments of the invention, best results are obtained by having a 1:1 imaging system, such as the prior art off-axis configuration shown in Figure 7, because of the increased flux density it provides at the target. For light collecting and condensing systems that do not produce a 1:1 image of the light source such as an arc lamp, the spot must be small compared to the size of

the target to incorporate the advantages of this invention as described below. In general, the type of light collection and imaging system is used is often determined by the size and dimensions of the target, the size and type of light guide, or the diameter and type of fiber optic output device, and all of their respective numerical apertures.

The light collection and imaging system illustrated in Figure 1 utilizes a concave toroidal reflector in off-axis configuration and produces approximately a 1:1, or unmagnified, image of the arc. However, because of inherent optical aberrations of such a 1:1 imaging system, maximum collection efficiency is achieved if the input cross section diameter of the optically transforming device, or light guide, is two to three times the size of the arc gap of the lamp. To collect as much total light as possible, the numerical aperture of the off-axis reflector is made as large as possible. For example, in an off-axis system like that in Figure 1, the NA is typically designed to be about 0.7, which produces a cone of light having an approximately 90 degrees solid angle. A larger numerical aperture system is possible and is only limited by the mechanical layout of the components. This angle is indicated as θ_1 in Figure 1. To increase the output further, a retro-reflector 5 is placed behind the lamp directly opposite the primary mirror. The retro-reflector will reflect light back through the lamp and focused through the arc, increasing the luminosity collectible by the primary mirror and increasing the total output at the

image point, the location of the target spot 6. To allow maximum coupling of light into a plastic fiber without damage, such as by heat for example, a fused bundle can be placed between the tapered cladded rod or tapered fused bundle and the input of the plastic fiber. If a tapered cladded rod is the optical transforming device, the fused bundle also facilitates scrambling the transmitting modes so as to produce a more uniform output for coupling to a single plastic fiber or a fiber bundle.

Aside from the use of a single large target, the invention also facilitates the more efficient coupling and transmitting of high intensity light through multiple fibers as the target. This not only includes a fiber bundle of hundreds or thousands of small diameter fibers, approximately 50 microns in diameter, but also bundles of larger fibers that can transmit sufficient amount of light for use in applications ranging from surgical illumination to commercial display lighting. As with a single fiber target, a multiple fiber target comprised of glass, quartz or plastic single fibers can be coupled directly, or, depending on the output from the particular type of light guide used, through intermediary fused bundles for minimizing damage to the fiber target. Typical fiber optic output devices can vary from a fiber bundle, comprised of small diameter optical fibers typically less than 80 microns diameter, to a single large diameter fiber optic typically made of plastic. For a target with multiple fibers where each fiber has a cross-sectional area of A(f), the total number of fibers of in the bundle is

necessarily less than the number obtained by dividing the cross sectional area of the output of the bundle by A(f).

Other embodiments of the present invention can be directed toward directing light to a plurality of fibers as the fiber optic output device wherein each fiber is typically greater than 0.1 mm diameter and less than 5 mm in diameter. This further embodiment of the invention provides for a distributed fiber optic lighting system wherein maximum light through each fiber optic is achieved by transforming the numerical aperture of the light collection system to match that of the individual fiber optics. In addition, the use of either a tapered fused bundle or a tapered cladded rod in conjunction with a fused bundle provides a nearly uniform output for coupling approximately the same amount of light into each individual optical fiber in the output bundle.

Intrinsically, a tapered cladded rod is more efficient in overall transmission than a tapered fused bundle. On the other hand, a tapered cladded rod requires a longer length to transform the NA completely than a tapered fused bundle, and requires a much longer length to scramble the modes of the rod. That is, the taper-length of a cladded rod, required for both changing the NA and scrambling the modes to produce a uniform output, is substantially longer than that required to change the NA only. The small diameter of the individual fibers in a tapered fused bundle, typically less than 80 microns, transform the angular and spatial profile within approximately 30 diameters of the

individual fiber. By contrast, a tapered cladded rod requires a much longer length to change both the numerical aperture and to produce a spatially uniform output.

Since relative to a cladded rod, a fused bundle is less efficient, the application of either as the light guide in embodiments of this invention will depend upon the dimensions of the fiber optic output device and the layout of the primary collector system. The final numerical aperture and overall efficiency for the transformation in the case of either a tapered fused bundle or tapered cladded rod is determined according to simple optical geometry, and varies according to the taper angle and length over which the taper occurs.

Given that the light source for each embodiment has a broad spectral output, wavelength discrimination is achieved in the invention through the use of dielectric coatings applied to the primary reflector of the light collection system and/or to either the input or output surface of the light transforming devices.

Example 1

Employing an off-axis imaging system having a 1:1 magnification, such as the one depicted in Figure 1, impacts upon the choice of the rest of the components. Because the primary mirror has a large angle of collection, the target image inherently experiences astigmatism and other optical aberrations which cause the image to be necessarily larger than the size of the arc gap. Maximum collection efficiency is achieved in a 1:1 imaging system if the input diameter of the optically

transforming device 8 is two to three times the size of the arc gap of the lamp and the input numerical aperture of the transforming device is similar to the numerical aperture of the of the incident light at the target spot. In Figure 1, the NA of the off-axis imaging system is approximately 0.7 and the NA of the optical transforming device is 0.66 or larger.

If the output device is 12 mm diameter single core plastic optical fiber with a 0.6 NA, any imaging system that produces a small focused spot that is less than approximately 6 mm would be suitable. For the 1:1 magnification present in an off-axis imaging system, a lamp with an arc gap of approximately 3 mm would be suitable to assure at least 80% collection of light at the target spot taking into account optical aberrations in the system which blur the image.

In general terms for this embodiment, the diameter, d_3, of the output fiber optic device should be approximately equal to or greater than the output diameter, d_2, of the tapered light guide and the input diameter of the tapered light guide, d_1, which is less than d_2 and d_3, must be approximately 2 times the length of the arc gap (or roughly equal to the inherent image spot size to arc gap ratio for some other type of imaging system of unspecified magnifying properties). In addition, the NA of the output fiber optic, NA3 should be about equal to NA2, the output NA from optical transforming device 8, and the input NA1, greater than NA2, should be similar to that of the light collection system to produce optimum overall efficiency. In

addition, the taper angle and length of element 8 is determined by equation 1.

Example 2

Given that the maximum collection efficiency of this invention depends on both the collecting and condensing/imaging optics and the design of the light guide, there is a family of configurations or preferred embodiments that will increase the amount of collected light transmitted through a fiber optic target depending on the size of the target. In an off-axis configuration, to obtain higher collection efficiency from the primary mirror requires that the effective NA of the primary mirror be increased. However, by increasing the solid angle over which light is reflected to the target, some rays will be magnified and some will be demagnified instead of imaged 1:1 as shown in Figure 2. For example, the ray r_3 as shown in the figure has the reflection point on the mirror closer to the lamp 1 than the target spot 6 and this will give a magnified image on the target. Ray r_4, as shown, has the reflection point at the mirror closer to the mirror than the lamp, will give a demagnified image. The overall image size, composed of the sum of all the rays, will increase the overall spot size from 1:1. To compensate for the increase in image size requires that the diameter of the input of the tapered rod or fused bundle be increased to maximize collection efficiency and should typically be somewhere between about 2 to about 3 times the length of the arc gap of the light source. Therefore, a non-uniform imaging

off-axis optical system such as that in Figure 2 having partial magnification of up to 3:1 with a lamp arc gap of 2 mm would produce a target spot diameter of approximately 6 mm, assuming no aberrations and require a 6 mm input for the tapered rod.

Example 3

Another way to collect and utilize light over a larger collection angle is to use an extended elliptical reflector as shown in Figure 3. Using this configuration, the majority of the light is collected by the reflector, but the magnification is not 1:1. Typically, such a configuration will have a magnification of no less than 3:1. The NA of light at the target in this case is still too large, about unity, to be coupled into a large diameter target, such as a fiber bundle or a large single plastic fiber each with an NA of about 0.5 to 0.6. In prior art systems incorporating elliptical collecting and condensing reflectors, the reflector is truncated and does not include the bolded portion of the reflector 3a in Figure 3. Light from the bolded portion in prior art systems cannot be used because the light collected from the high NA portion would be of too high an NA and will not couple into typical fiber targets having NA typically around 0.6 or smaller. In this embodiment of the invention, transformation of a high NA light to lower NA with a tapered cladded rod or tapered fused bundle such as the light guide 8 allows additional light flux, transformed from higher to lower NA, to be coupled into the fiber optic target. Again, the input diameter of the tapered light guide would have to be larger than

the arc gap of the source, typically at least three times larger, for such a configuration.

Example 4

Light transmission through the target is optimized if the output numerical aperture of the tapered light guide is less than the numerical aperture of the fiber optic output device. The NA of the output optical fiber is related to the input NA of the tapered light guide by relationship (1), and the input NA of the tapered light guide is typically equal to or less than that of the optical collecting and imaging system. The length of the tapered optical transforming device is determined by ratio of input and output NA's of the device and whether a fused bundle or cladded rod is tapered. In either case, the input NA of the tapered light guide must be at least equal to the NA of the primary collector system at the target spot for maximum collection efficiency at the target.

For example, a 5-inch long tapered cladded rod is used as a light guide. The tapered cladded rod has an input diameter of about 2.5 mm and an output diameter of about 4 mm. This rod transforms light with an input NA of about 0.7 (such as from a primary collection system as described in Example 1) to an output NA of about 0.45. This output light couples efficiently to an output fiber optic bundle having a 5 mm diameter and NA of 0.5. Compared to a cladded rod having no taper, the increase in output through the output fiber bundle is about 15% and can be increased

further by dielectrically coating the input and output ends of the taper with an anti-reflection coating.

Example 5

In another embodiment, a tapered fused bundle having an input end diameter of about 6 mm and an output end diameter of about 10 mm is used to couple light from a small arc lamp into a large optical fiber core, approximately 12 mm in diameter. Compared with a fused bundle without taper, the output from the optical fiber core increases by 22%.

The invention having been thus described, it will be apparent to those skilled in the art that the embodiments of the invention may be varied and modified in many ways without departing from the spirit and scope of the invention. Therefore, any and all such modifications are intended to be included within the scope of the following claims.

What is claimed is:

1. A system for increasing coupling of light into a fiber optic device comprised of

- a light-providing electromagnetic collecting and condensing system having a lamp with arc gap size S and having an effective numerical aperture NA_0;

- a fiber optic light guide member which is a negative lens, or a light guide having an input end for receiving light from said collecting and condensing system and an output end for outputting light from the light guide, said input end of the light guide having an input numerical aperture NA_1 and an input diameter d_1, said output end of the light guide having an output numerical aperture NA_2, and an output diameter d_2, wherein said NA_1 is less than or equal to said NA_0, said NA_2 is less than said NA_1, said S is less than said d_1, and said d_1 is less than said d_2; and

- a fiber optic output device for receiving light from the output end of the light guide and outputting the light, said output device having a diameter d_3 and a numerical aperture NA_3, wherein said NA_3 is greater than or equal to said NA_2, and said d_3 is greater than or equal to said d_2.

2. A system according to claim 1, wherein said fiber optic light guide comprises a tapered cladded rod.

3. A system according to claim 1, wherein said fiber optic light guide comprises a tapered fused optical fiber bundle.

4. A system according to claim 1, wherein said light guide comprises a hollow tube having an reflective inner surface.

5. A system according to claim 5, wherein said hollow tube comprises a compound parabolic concentrator.

6. A system according to claim 1, wherein said fiber optic light guide member is a negative lens.

7. A system according to claim 6, wherein said system further comprises a cylindrical cladded rod or fused bundle interposed between said negative lens and said output device to transmit light from the light guide to the output device.

8. A system according to claim 1, wherein said system further comprises a fused fiber optic bundle interposed between said light guide and said output device to transmit light from the light guide to the output device.

9. A system according to claim 1, wherein said electromagnetic collecting and condensing system comprises at least one spherical concave reflector.

10. A system according to claim 1, wherein said electromagnetic collecting and condensing system comprises at least one toroidal concave reflector.

11. A system according to claim 1, wherein said electromagnetic collecting and condensing system comprises an ellipsoidal concave reflector.

12. A system according to claim 1, wherein said electromagnetic collecting and condensing system includes a retro-reflector.

13. A system according to claim 1, wherein said fiber optic output device comprises an optical fiber.

14. A system according to claim 1, wherein said fiber optic output device comprises a plurality of optical fibers.

15. A system according to claim 14, wherein said fiber optic output device comprises a fused bundle of said plurality of optical fibers.

16. A system for increasing coupling of light into a fiber optic device comprised of

- an electromagnetic radiation source, said source providing radiation having a output spot of diameter S and having a numerical aperture NA_0;

- a fiber optic output device for transmitting light having a diameter d_3 and a numerical aperture NA_3; and

- an optical transforming device for decreasing the numerical aperture and increasing the diameter of the output spot of the radiation from the radiation source and directing the radiation into the fiber optic output device, said transforming device being a negative lens, or a device having an input numerical aperture NA_1, an input diameter d_1, an output numerical aperture NA_2, and an output diameter d_2, wherein said NA_1 is less than or equal to said NA_0, said NA_2 is less than said NA_1, said S is less than said d_1, and said d_1 is less than said d_2, said NA_3 is greater than or equal to said NA_2, and said d_3 is greater than or equal to said d_2.

17. A system according to claim 16, wherein said optical transforming device comprises a tapered cladded rod.

18. A system according to claim 16, wherein said optical transforming device comprises a tapered fused optical fiber bundle.

19. A system according to claim 16, wherein said optical transforming device comprises a hollow tube having an reflective inner surface.

20. A system according to claim 19, wherein said hollow tube comprises a compound parabolic concentrator.

21. A system according to claim 16, wherein said transforming device is a negative lens.

22. A system according to claim 16, wherein said system further comprises a cylindrical cladded rod interposed between said optical transforming device and said output device to transmit light from the transforming device to the output device.

23. A system according to claim 16, wherein said system further comprises a fused fiber optic bundle interposed between said optically transforming device and said output device to transmit light from the transforming device to the output device.

24. A system according to claim 16, wherein said electromagnetic radiation source further comprises a spherical concave reflector and arc lamp.

25. A system according to claim 16, wherein said electromagnetic radiation source comprises a toroidal concave reflector and arc lamp.

26. A system according to claim 16, wherein said electromagnetic radiation source comprises an ellipsoidal concave reflector and arc lamp.

27. A system according to claim 16, wherein said electromagnetic radiation source comprises a primary reflector and a retro-reflector.

28. A system according to claim 16, wherein said fiber optic output device comprises an optical fiber.

29. A system according to claim 16, wherein said fiber optic output device comprises a plurality of optical fibers.

30. A system according to claim 29, wherein said fiber optic output device comprises a fused bundle of said plurality of optical fibers.

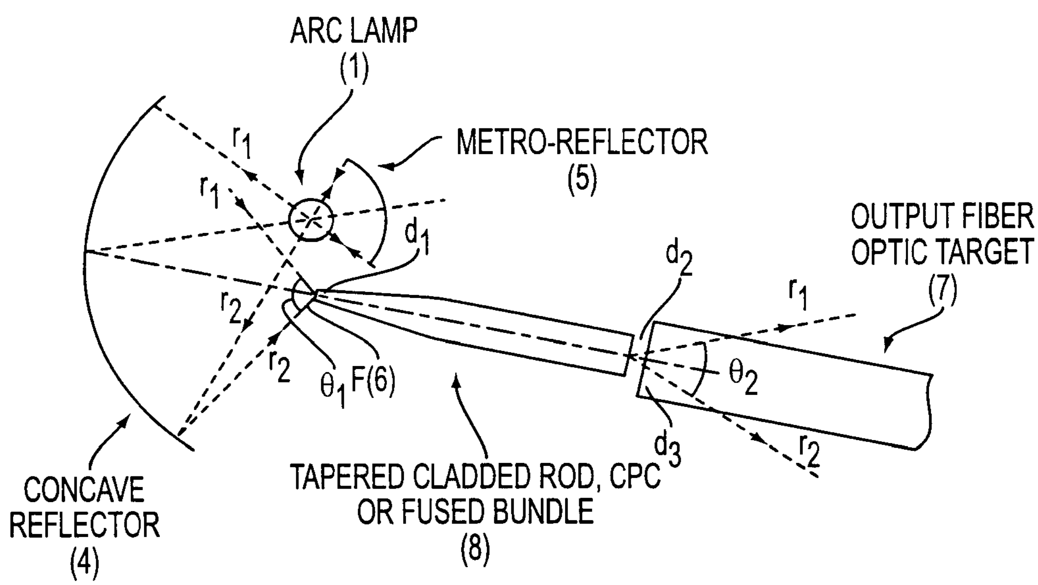
31. A system according to claim 1, wherein said light guide comprises a solid compound parabolic concentrator.

32. A system according to claim 1 wherein said light-providing system comprises a lamp selected from the group consisting of xenon, mercury, mercury xenon, and metal halide lamps.

33. A system according to claim 1, wherein said electromagnetic collecting and condensing system produces approximately a 1:1 image of said arc gap size S at said input of said light guide member.

34. A system according to claim 16, wherein said optical transforming device comprises a solid compound parobolic concentrator.

35. A system according to claim 16, wherein said electromagnetic radiation source further comprises approximately a 1:1 optical imaging system.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TAPERED CLADDED ROD, CPC
OR FUSED BUNDLE
(8)

FIG. 1

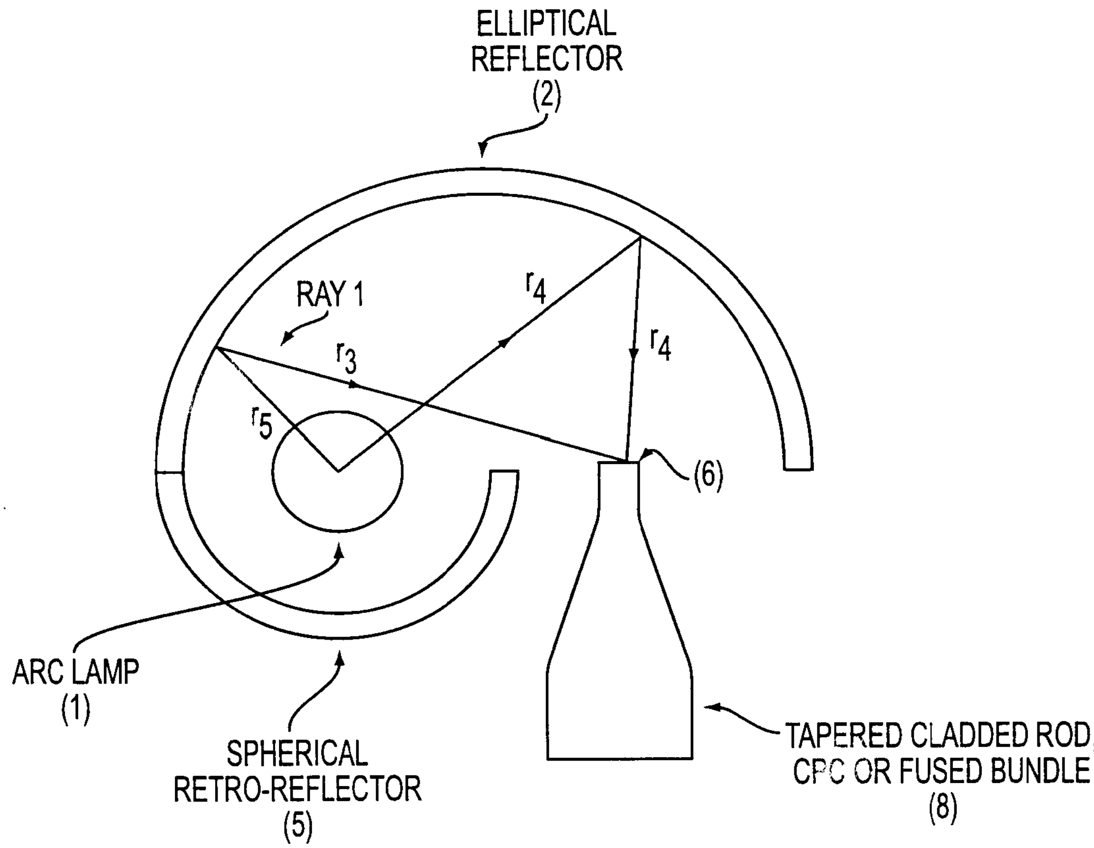
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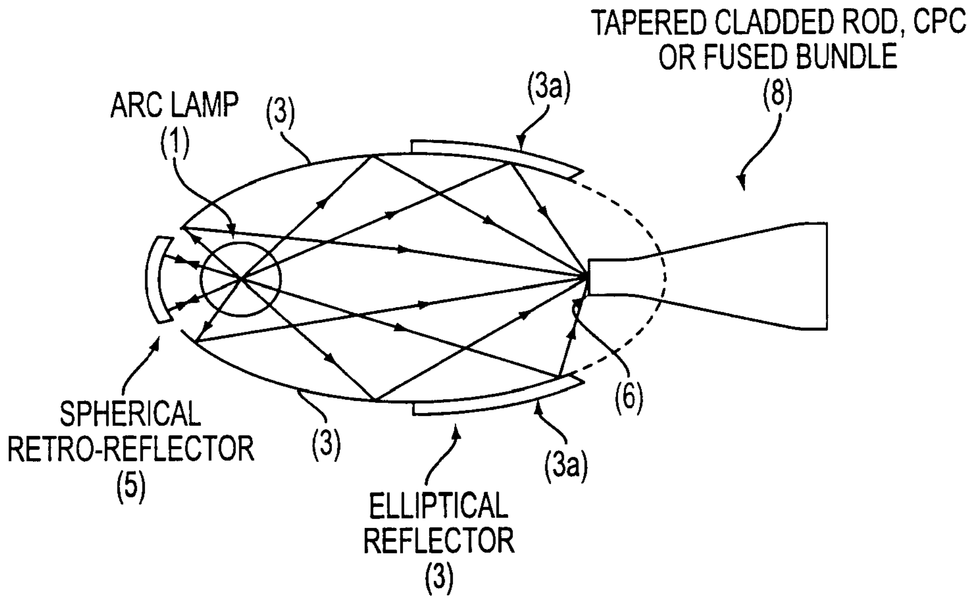
FIG. 2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REFLECTOR
(3)

FIG. 3

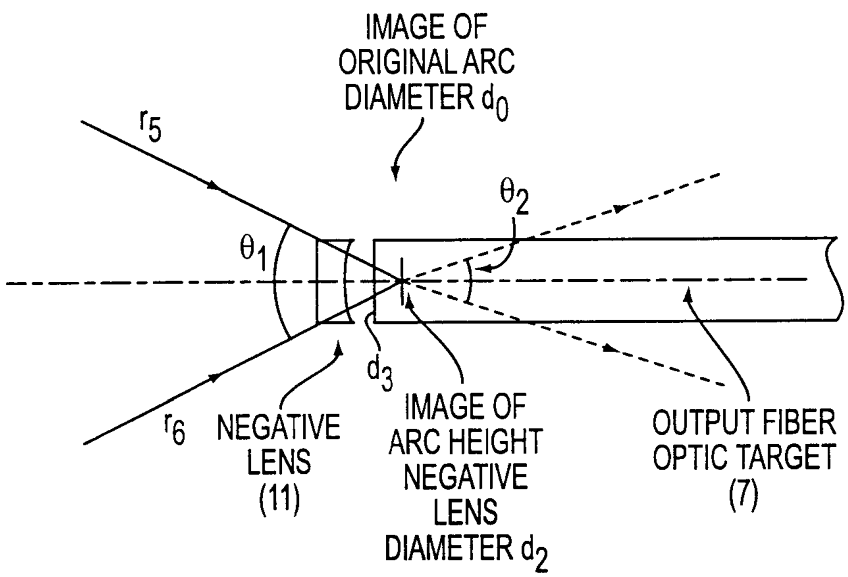
IMAGE OF
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DIAMETER d_0
r_5
θ_2
θ_1
d_3
r_6
NEGATIVE
LENS
(11)
IMAGE OF
ARC HEIGHT
NEGATIVE
LENS
DIAMETER d_2
OUTPUT FIBER
OPTIC TARGET
(7)

FIG. 4

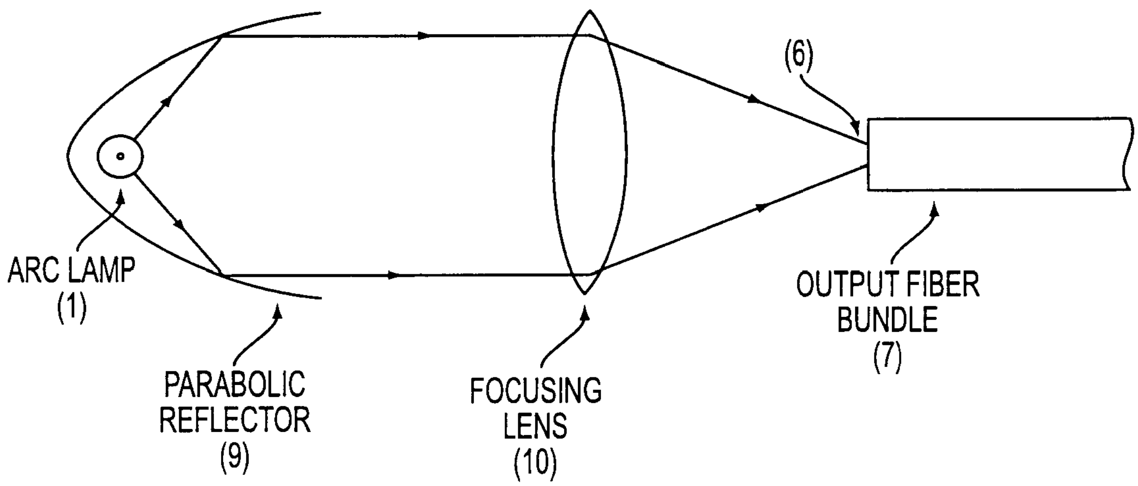

FIG. 5
(PRIOR ART)

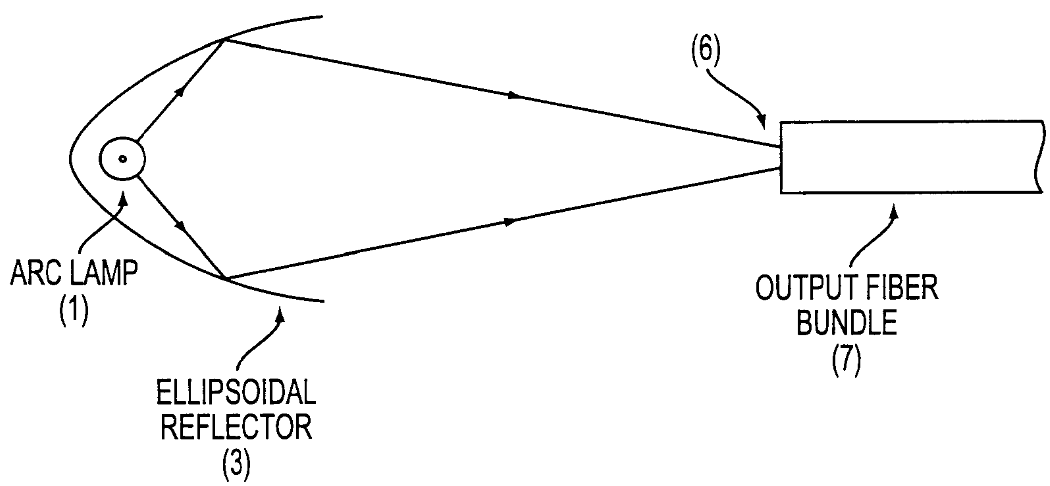

FIG. 6
(PRIOR ART)

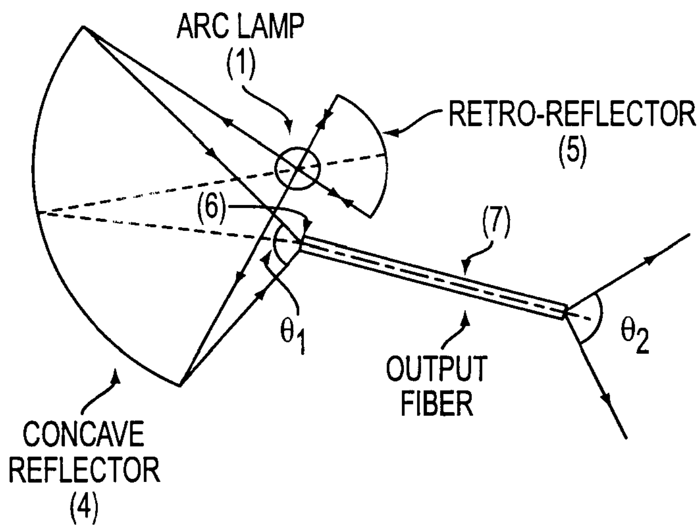

FIG. 7
(PRIOR ART)

INTERNATIONAL SEARCH REPORT

Inte onal Application No
PCT/US 00/04700

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/42 F21V8/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B F21V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 July 2000	18/07/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	von Moers, F

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/04700

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

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